Finite element simulation of multi-gripper flexible stretch forming

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Abstract

Multi-gripper flexible stretch forming is a novel sheet metal forming process aimed at improving the conformability of sheet metal to forming die, material utilization and forming quality of sheet metal. Straight jaws in traditional stretch forming machines are replaced by a pair of opposed clamping mechanisms movable relative to each other during the forming process. In the present study, a wave-like surface part was selected as the study object, and the forming processes of traditional stretch forming and multi-gripper flexible stretch forming were performed using a commercially available finite element analysis software to show their influences on conformability of sheet metal. In addition, three levels of transition lengths in multi-gripper flexible stretch forming were chosen to investigate their influence on forming results. The simulation results show that multi-gripper flexible stretch forming would result in an easier conformability of sheet metal than traditional stretch forming. It is also found that the sheet metal can be formed without a transition length, which could significantly improve the material utilization. In addition, the simulation results show that a shorter transition length would result in a smaller maximum strain in the forming zone, which may provide a useful guidance on choosing the transition length of sheet metal.

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Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keyword: Stretch forming; Conformability; Transition zone; Flexible forming

1. Introduction

The stretch forming process is a process used to shape sheet metal parts, generally in small series, which has the following advantages such as low tooling cost (only male tools are needed), short manufacturing cycle, simple processing and low elastic return. However, the low flexibility of the loading mechanism and clamping mechanism in traditional stretch forming machine would easily result in the following forming defects such as incomplete...
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conformance of sheet metal to forming die, wrinkle or even material failure. In addition, a large processing allowance (normally 200-500 mm) named transition zone is also necessary, leading to a quite low material utilization.

Under such background, it has been put forward urgent demands on increasing the flexibilities of stretch forming. Stretch forming flexibilities are mainly embodied on the flexibilities of forming die and loading mechanism, and corresponding researches have been conducted on both sides but mainly focused on the flexibility of forming die.

The concept of reconfigurable tooling can be tracked back to 1863 in a US patent, in which Cochrane (1863) invented a machine for bending sheet metal into various forms of mold required in naval construction. However, it was attracted wide concern in academic and industrial fields until the late 1960s, began with the pioneering work of Nakajima (1969). Starting in 1980 and continuing into the late 1990s, scholars at Massachusetts Institute of Technology conducted systematic investigation on reconfigurable tooling system. In the authors’ previous work, a concept of multi-point forming was proposed by Li et al. (1992) in 1992. Later, Li and his coworkers conducted deep and systematic research focused on mechanism design, forming characteristics and forming defects in multi-point forming. As the researches mentioned above are mainly focused on the flexible forming die, detailed presentations about them are not listed here.

Based on the research achievements of multi-point forming, Li and his co-workers had developed a type of multi-gripper flexible stretch forming apparatus (shown in Fig. 1a). Li et al. (2011) addressed mechanism design and forming characters of this type of multi-gripper flexible stretch forming apparatus, and conducted comparative analyses between the apparatus and traditional stretch forming machines. Three different clamping modes in stretch forming were investigated to shown their influences on forming results by Chen et al. (2011), and the simulation results revealed that the discrete clamping mode would result in a better forming quality of simulated part and corresponding validation was conducted on self-developed prototype machine. Chen et al. (2012) investigated the influences of different numbers of grippers on stress, thickness and configuration of edge line of the clamping zone in simulated parts, and pointed out the forming quality of the simulated part improved with the gripper number increased. Later, Li and his co-workers developed another type of multi-gripper flexible stretch forming apparatus (shown in Fig. 1b) to further improve the conformability of sheet metal and material utilization. Peng et al. (2011) conducted comparative analyses on the stress, thickness and springback of the simulated parts between two kinds of multi-gripper flexible stretch forming processes. However, the influences of processing parameters of the newly developed multi-gripper flexible stretch forming apparatus on forming results have not been investigated.

In the paper, a wave-like forming die was selected as study object, and the forming processes of traditional stretch forming and multi-gripper flexible stretch forming were performed using a commercially finite element analysis software to show their influences on conformability of sheet metal to the forming die. In addition, three levels of transition lengths in multi-gripper flexible stretch forming were chosen to investigate their influences on forming results.

Fig. 1. Schematics of two types of multi-gripper flexible stretch forming apparatus: (a) old type; (b) new type.
2. Forming apparatus

Multi-gripper flexible stretch forming is a novel sheet metal forming process derived from traditional stretch forming and multi-point forming technology, in which the Pascal’s Law of multi-cylinder hydraulic system, strain hardening and minimal resistance force of the material are employed. Fig. 2 shows the newly developed multi-gripper flexible stretch forming apparatus by Dieless Forming Technology Center of Jilin University. A stretch forming apparatus of the type mainly consists of a pair of opposed discrete clamping mechanisms, a set of multi-point die, three rows (horizontal, inclined and vertical) of hydraulic cylinders installed on each side of the multi-point die, and a frame. The hydraulic cylinders in the same row are controlled by a common electromagnetic direction valve to simplify the control system, therefore, they will produce the same tensile force during the forming process. During the forming operation, the discrete clamping mechanisms would make real-time position adjustment to assume a contour roughly in the shape of the curved surface of the die, which results in an easy conformability of sheet metal to the forming die.

3. FE model

3.1. Material model

A deep-drawing cold-rolled steel (ST14) with a thickness of 2 mm was considered in the current study. The relevant mechanical properties are: density $\rho = 7.85$ g/cm$^3$, elastic modulus $E = 207$ GPa, Poisson’s coefficient $\nu = 0.28$, initial yield strength $\sigma_y = 176.3$ MPa, Swift coefficients: $K = 596$ MPa and $n = 0.247$.

The material is modeled as elastic-plastic where the elasticity is taken to be isotropic and the plasticity is modeled as anisotropic using the Hill quadratic anisotropic yield criterion. In ABAQUS, anisotropic yield behavior is modeled through the use of yield stress ratios, $R_{ij}$. In the present study $R_{00}$, $R_{45}$, $R_{90}$ equals to 1.88, 1.4 and 2.23 respectively. However, the sheet anisotropy is commonly defined by the plastic strain ratios of width strain to thickness strain (i.e. $r$-value) in the cases of sheet metal forming applications. Therefore, mathematical relationships are then necessary to convert the strain ratios to stress ratios that can be input into ABAQUS.

3.2. Models of FE simulation

ABAQUS/Explicit, an explicit dynamic code, was chosen to simulate the processes of traditional stretch forming and multi-gripper flexible stretch forming, in which complicated contact problems can be solved with greater ease and less system resources are required than implicit procedure. Fig. 3 shows the finite element models of traditional stretch forming and multi-gripper flexible stretch forming processes. For both types of stretch forming processes, the dies were modeled with R3D4 elements as well as the clamping parts and the grippers. The blank sheet was modeled with S4R elements and the default hourglass control algorithm for the sheet metal was adopted. In addition, the hydraulic cylinders were modeled with connectors to simplify the finite element model.
General contact algorithm was adopted and the frictions at the interfaces were assumed to follow Coulomb’s model. The friction coefficient between the blank and die was considered as 0.1. As there was no relative slip, the tangential behavior at the interfaces between the grippers and the blank sheet was modeled with the Rough friction formulation in both traditional stretch forming and multi-gripper flexible stretch forming.

In view of the symmetry of the model and the computational time, only a quarter of the finite element models were built. The symmetry axes of the sheet metal were constrained with symmetry boundary conditions and the die was fixed in all finite element simulations.

![Fig. 3. FE model of two kinds of stretch forming processes: (a) traditional stretch forming; (b) multi-gripper flexible stretch forming.](image)

### 4. Results and discussion

#### 4.1. Conformability of sheet metal to forming die

Fig. 4 shows the shape error maps (along z axis before springback) of the simulated parts of different stretch forming processes under the condition of with a transition length of 50 mm. It is seen clearly from Fig. 4b that the maximum error of the simulated part in multi-gripper flexible stretch forming is located near the edge area of the forming zone which has a value of 0.442 mm. Therefore, it can be considered that the sheet metal has been completely conformed to the shape of the forming die in view of the mesh size is 8 mm × 8 mm for the sheet metal and which would lead to a small deviation. However, the maximum error of the simulated part in traditional stretch forming (shown in Fig. 4a) is 8.28 mm and which indicates that the sheet has not completely conformed to the shape of the die. Therefore, it is concluded that multi-gripper flexible stretch forming would result in better conformability of sheet metal than traditional stretch forming under the same transition length.

![Fig. 4. Shape error maps along z axis (before springback) of the simulated parts: (a) traditional stretch forming; (b) multi-gripper flexible stretch forming.](image)
4.2. Influences of the transition length on forming results

In practical application, the loading sequence of hydraulic cylinders is very complicated. Fig. 5 shows two representative loading paths used in multi-gripper flexible stretch forming, in which $F_h$, $F_t$, and $F_v$ are exerted by horizontal, tilting and vertical hydraulic cylinders respectively. However, the influences of loading paths on the forming results will not be discussed here. In this paper, horizontal-vertical loading path is used to simplify the finite element model, i.e. pre-stretch the sheet using horizontal cylinders first and then wrap the sheet around the forming die using vertical cylinders.

The forming forces when the sheet metal completely conformed to the die under different transition lengths are shown in Table 1. It is clearly seen that the vertical force increases with the transition length increased. Therefore, it can be concluded that a shorter transition length would result in a smaller forming force.

![Fig. 5. Representative loading paths used in multi-gripper flexible stretch forming: (a) horizontal-vertical loading path; (b) horizontal-tilting-vertical loading path.](image)

![Table 1. Forming force under different transition lengths.](image)

<table>
<thead>
<tr>
<th>Transition Length (mm)</th>
<th>Horizontal force (KN)</th>
<th>Vertical Force (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>45</td>
<td>23</td>
</tr>
<tr>
<td>100</td>
<td>45</td>
<td>27</td>
</tr>
<tr>
<td>300</td>
<td>45</td>
<td>35</td>
</tr>
</tbody>
</table>

Fig. 6 shows the maximum principal strain contour plots of the simulated parts under different transition lengths. It is seen clearly that the maximum strain in the forming zone increases with the transition length increased. However, the maximum strain in the transition zone decreases the transition length increased. It is because the forming force increases with the transition length increased, thus resulting in a larger maximum strain in the forming zone. However, on the other perspective, a shorter transition length would result in a more severe local deformation in the region contacted with the grippers and which would cause a larger strain in the transition zone and increase the risk of material failure.

![Fig. 6. Maximum principal strain contour plots of the simulated parts under different transition lengths: (a) 0; (b) 100 mm; (c) 300 mm.](image)
5. Conclusions

Numerical simulations of traditional stretch forming and multi-gripper flexible stretch forming processes have been performed using a dynamic explicit finite element method. In addition, the influences of transition length on forming force and strain distribution in multi-gripper flexible stretch forming were also taken into consideration. The main points can be concluded as follows:

1. Compared to traditional stretch forming, multi-gripper flexible stretch forming would result in an easier conformability of sheet metal to the forming die under the same transition length.

2. The sheet metal can be formed into the desired shape under the condition of without a transition length by utilizing multi-gripper flexible stretch forming, which would significantly improve the material utilization. In addition, the shorter the transition length is, the smaller the forming force will be.

3. In multi-gripper flexible stretch forming, a shorter transition length would result in a smaller strain in the forming zone, but a larger strain in the transition zone, which provides a useful guidance on choosing the transition length of sheet metal.

Acknowledgements

The authors would like to acknowledge the financial support provided by the EU Sixth Research Framework (ASTS-CT-2006-030877).

References